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Can Oscillating Physics Explain an Apparently Periodic Universe?

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Abstract

The striking, unexpected feature of the pencil-beam red shift survey recently reported by Broadhurst, Ellis, Koo and Szalay[1] (BEKS) is a periodicity in the galaxy distribution of 128 h^{-1} Mpc. Here we consider whether the apparent spatial periodicity might really be an observational effect induced by spatially uniform but temporally oscillating physical "constants" of nature. An oscillation in the gravitational constant would introduce oscillations in the linear red shift-distance relation (Hubble law). An oscillation in the Rydberg, due to a variation in the fine structure constant or the electron mass, would introduce oscillations in atomic lines which affect red shift measurements in a periodic manner. Periodic variation in galactic luminosities (e.g., due to oscillation in the coupling and/or masses of a weakly interacting particle such as a neutrino or axion) could also result in an apparent periodicity in the galaxy survey. In all cases, a crucial prediction is the occurrence of peaks in the red shift distribution lying on approximately concentric spherical shells with periodically spaced radii. Oscillation models can be decisively tested by a combination of cosmological observations and laboratory measurements of fundamental constants.

A natural method of inducing oscillations of a fundamental physical "constant" is to suppose that it is really a function of a fundamental scalar field, ϕ, whose average value $\langle\phi\rangle$ is fixed by the minimum of its potential and which oscillates about $\langle\phi\rangle$ [2]. To reproduce the BEKS data, ϕ must be a field with an ultra-low mass (a soft boson) coherently oscillating with a period $c\tau \simeq L = 128\ h^{-1}$ Mpc corresponding to a mass $m = \mathcal{O}(10^{-31}$ eV), where the present Hubble parameter is $H_0 = 100\ h$ km sec^{-1} Mpc^{-1}. Recently, Morikawa [3] has proposed an explanation of the BEKS data wherein the dominant dark matter is an oscillating soft-boson field non-linearly coupled to gravity, which induces oscillations in the Hubble parameter. Our more general analysis considers four distinct scenarios: (a) oscillating dark matter fields; (b) oscillating G; (c) oscillating atomic lines (i.e., Rydberg); and (d) oscillating galactic luminosities.

The common feature of scenarios (a)-(c) is that the actual red shift measured by an observer today, z, is related to the red shift observed in the absence of oscillations, z_0, by:

$$\frac{dz}{dz_0} = 1 + \mathcal{A}\cos\left[\frac{2\pi}{L}(t - t_0) + \psi\right], \tag{1}$$

where $t_0 = 2H_0^{-1}/3$ is the present time and ψ is a phase. (For simplicity, only contributions to lowest orders in z_0 and the amplitude $\mathcal{A}$ will be presented in this analysis, although it is straightforward to generalize these results.) For uniform galaxy density per comoving volume, n_0, the number of galaxies dN in a solid angle $d\Omega$ with red shift between z and $z + dz$ is modulated compared to the distribution in the absence of oscillations via

$$\frac{dN}{z^2 dz d\Omega} = \left(\frac{dN}{z_0^2 dz_0 d\Omega}\right)\frac{dz_0}{dz} \tag{2}$$

where we have used the fact that $z^2 \approx z_0^2$ to lowest order. Owing to the modulation factor, dz/dz_0, even for a spatially uniform galaxy density, an observer would see an apparent variation in the density of galaxies which is isotropic and has peaks lying on concentric spherical shells at periodically spaced radii.

In Fig. 1, we show the modulation factor and the one–dimensional galaxy pair correlation function predicted for a pencil-beam survey with $\mathcal{A} = 0.8$ and $\psi = 0$. An amplitude of at least 0.5 and phase $\psi \approx 0$ seem to be required to reproduce the BEKS results. This is a crude estimate since we have not incorporated the observational selection function and we have assumed $\mathcal{A}$ to be time-independent. Also, a more realistic analysis would include the known clustering of galaxies and the random distribution of voids as observed in the wider-angle, shallower CfA survey [4]. Their inclusion will produce a distortion of the concentric shells, especially apparent for the nearest ones. Consequently, small differences in the period measured in other angular directions are to be expected.

Motion with respect to the cosmic rest frame affects red shifts:

$$z = z_{OBS} + \mathbf{v}_{OBS} \cdot \hat{n} - \mathbf{v}_{GAL} \cdot \hat{n} = z_{OBS} + v_{OBS} \cos\theta - v_{GAL} \cos\theta', \qquad (3)$$

where z is the true cosmological red shift, z_{OBS} is the red shift measured by the observer whose velocity is $\mathbf{v}_{OBS}$, $\mathbf{v}_{GAL}$ is the peculiar velocity of the galaxy, and $\hat{n}$ points towards the source galaxy. As is apparent from Eq. 3, peculiar velocities of distant galaxies, which are not well known at present and which vary from galaxy to galaxy, can make the shells appear aspherical. The earth's motion with respect to the microwave background has a uniform effect. Since the argument of the oscillatory term is $2\pi(t-t_0)/L \approx$

$-2\pi H_0^{-1}z/L$, the net effect is a direction-dependent change in phase:

$$\delta\psi(\theta) = -\frac{2\pi H_0^{-1}}{L} v_{OBS}\cos\theta. \tag{4}$$

The apparent center of the spherical pattern is shifted but the period is unchanged. From the dipole anisotropy of the microwave background [5], $\mathbf{v}_{OBS}$ is known to be 360 km sec^{-1} directed 40 degrees from the North Galactic Pole. For the BEKS survey, then, $\delta\psi \approx .02(2\pi \text{ rad})(128\ h^{-1}\ \text{Mpc}/L)$. The BEKS survey suggests a larger shift which may not be statistically insignificant or may be dominated by asphericity in the nearest shells suggested above.

(a) *Oscillating Dark Matter Field* [3, 6]: Suppose that the dominant component of dark matter is a massive scalar field, ϕ, which oscillates in a harmonic potential due to its mass, $m^2\phi^2$. The Hubble parameter, H, energy density, $\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2$, and pressure, $p = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2$, are related by

$$H^2 = \frac{8\pi G\rho}{3}; \quad \frac{d(\rho a^3)}{dt} = -p\frac{d(a^3)}{dt}; \tag{5}$$

where $a(t)$ is the scale factor. If $\phi = \beta\cos(mt)/a^{3/2}$ then, averaged over one cycle, $p = 0$, $\rho_0 \approx m^2\beta^2/a^3$ and $H \equiv \bar{H} = (8\pi G\rho_0/3)^{\frac{1}{2}}$. However, within one cycle, the pressure oscillates between ρ and $-\rho$, $p = -\rho_0\cos 2mt$. From Eq. 5, the correction to ρ_0 is $\rho = \rho_0[1 + \sin 2m(t-t_0)/mt]$, and hence:

$$H = \bar{H}\left(1 + \frac{3\bar{H}}{4m}\sin\left[2m(t-t_0)\right]\right). \tag{6}$$

Since $H \equiv \dot{a}/a$ and $1 + z \equiv a^{-1}$, it is straightforward to show that

$$\frac{dz}{dz_0} = 1 + \frac{3\bar{H}}{4m}\cos\left[2m(t-t_0)\right]; \tag{7}$$

i.e., $\mathcal{A} = 3\bar{H}/4m$. Here is the rub: The ratio $\bar{H}/m$ is fixed by the observed period in the BEKS sample: $L = \pi/m = 128\ h^{-1}$ Mpc $\Rightarrow \mathcal{A} = 0.010$. Since this amplitude is small compared to the required value, $\mathcal{A} \gtrsim .5$, we conclude that it is unnecessary and insufficient to introduce a soft-boson field as the dominant source of dark matter to explain the BEKS data.

(b) *Oscillating Gravitational Constant, G*: If G is time-dependent,

$$H^2 = -\frac{\dot{G}}{G}H + \frac{8\pi G\rho}{3}. \tag{8}$$

Supposing that $G = G_0 + G_1 \cos[2m(t-t_0)+\psi]$, the leading correction to the Hubble parameter is $H \approx \bar{H}[1 - \frac{1}{2}(\dot{G}/G\bar{H})]$ and

$$\frac{dz}{dz_0} = 1 - \frac{\dot{G}}{2G\bar{H}} = 1 - \frac{mG_1}{\bar{H}G_0}\cos[2m(t-t_0)+\psi] \Longrightarrow \mathcal{A} = -\frac{mG_1}{\bar{H}G_0}. \tag{9}$$

The chief constraint comes from limits on $\dot{G}/G$ based upon the Viking radar-echo experiments [6]. The most conservative estimates of the systematic errors lead to $\dot{G}/GH_0 \le .3h^{-1}$. From Eq. 9, this limit implies $|\mathcal{A}| \lesssim .15h^{-1}$. On the face of it, this constraint causes the model to fall marginally short of the desired amplitude. However, we have included only the lowest order (i.e., linear) effects of $\dot{G}/G$ on H and we have not allowed for possible time-variation of the amplitude $\mathcal{A}$. Also, we come close enough that the Viking experiment, whose systematic errors are dominated by possible unknown perturbations of the Mars orbit, merits renewed consideration.

The simplest method for implementing the model is to introduce a scalar field, ϕ, with non-minimal coupling to the scalar curvature $\mathcal{R}$ of the form $[(16\pi G_0)^{-1} + \xi\phi^2]\mathcal{R}$ [3]. Such terms appear in virtually every model that unifies gravity with the other fundamental forces, and especially in recent attempts to implement inflationary cosmology [7]. If ϕ is oscillating in a harmonic potential, $m^2\phi^2$, with amplitude β, then $G_1 = \xi\beta^2$. Note that β

may be small so that ϕ is not the dominant dark-matter field provided that the curvature coupling ξ is sufficiently large.

An important variant of this approach is a scalar field with $\xi < 0$ and with mass $m \ll H_0$ or zero. In this case, the equation of motion for ϕ is [7]

$$\ddot{\phi} + 3H\dot{\phi} \approx -(\xi H_0^2)\phi. \tag{10}$$

The field oscillates about zero with an effective (time-dependent) mass equal to $\sqrt{\xi}H_0$. By choosing $\xi \approx 6400$, the period matches the BEKS distribution. The attractive feature is that the ultra-light soft-boson mass scale does not have to be fixed by hand from the outset; rather, it is naturally generated by couplings to the scalar curvature.

(c) *Oscillating Atomic Lines*: An oscillation in the Rydberg constant, $Ry = \alpha^2 m_e c/2h$, produces a periodic variation in the wavelength of the radiation emitted by galaxies (and all systems). Such an effect could arise from oscillations in α or m_e induced by coupling a soft-boson field to $F_{\mu\nu}F^{\mu\nu}$ or $\bar{\psi}_e\psi_e$ [2]. The expansion rate is unchanged but the frequency of the emitted radiation varies as $\nu_E = \nu_*[1 + \varepsilon\sin(m(t-t_0)+\psi)]$, where ε is the amplitude of the oscillation in Ry and m is the mass of the soft-boson. The measured (apparent) red shift (z) is related to the actual cosmological red shift (z_0) by:

$$\frac{dz}{dz_0} = 1 - \frac{m\varepsilon}{H_0}\cos[m(t-t_0)+\psi]. \tag{11}$$

For a period $L = 128\ h^{-1}$ Mpc, the mass must be $m = 2\pi/L = 3.1\,h \times 10^{-31}$ eV. To obtain an amplitude $\mathcal{A} = m\varepsilon/H_0 \gtrsim 0.5$, we require only

$$\varepsilon \equiv \frac{\delta\, Ry}{Ry} = \frac{\delta\, m_e}{m_e} + 2\frac{\delta\alpha}{\alpha} \gtrsim 3 \times 10^{-3}. \tag{12}$$

While existing limits address monotonic variations in α and m_e, they also appear to restrict oscillations. The Oklo natural reactor[10] constrains the difference between α today and α during reactor operation (1.8×10^9 yr ago; duration $\approx 2 \times 10^5$ yr) to be $\delta\alpha/\alpha < 10^{-8}$. Comparison of the laboratory lifetime of the rhenium isotope ^{187}Re with those inferred for geologic and meteoritic samples[10], implies $\delta\alpha/\alpha < 2 \times 10^{-5}$. These arguments can be adapted to constrain variations in m_e, although this point has not been made previously. First, variations in m_e necessarily imply variations in $\delta\alpha$ through QED radiative corrections: $\delta\alpha/\alpha = 2\alpha(\delta m_e/m_e)/3\pi$. Hence the Oklo limit on α yields $\delta m_e/m_e \lesssim 6.5 \times 10^{-6}$. Second, m_e directly affects the kinetic energy available for the decay products of ^{187}Re, leading to the limit $\delta m_e/m_e \lesssim 6 \times 10^{-4}$. Finally, a nonterrestrial limit arises from the coincidence of red shifts deduced from 21 cm (hyperfine, $\Delta E \sim \alpha^4 m_e^2/m_N$) and ordinary ($\Delta E \sim Ry$) transitions in absorping gas clouds in front of 7 QSO's ($.4 < z < 2.1$) [11]: $2\delta\alpha/\alpha \sim \delta m_e/m_e < 3 \times 10^{-4}$. While there are possible mechanisms for evading all these limits,[1] the oscillating Rydberg scenario seems problematic.

(d) *Oscillating Galactic Luminosities:* In a survey of the BEKS type an apparent periodicity could be induced by variations in galactic luminosities alone. The BEKS galaxies tend to be the most luminous at a given red shift, lying in the region of the luminosity distribution of galaxies where the number density of galaxies falls off exponentially[12]. Hence, a periodic variation in the intrinsic brightness of galaxies by a factor of two or so could produce the periodic variation seen in the BEKS survey.

One means of varying galactic luminosities is to modulate stellar luminosities. This might occur through oscillations in fundamental constants; or,

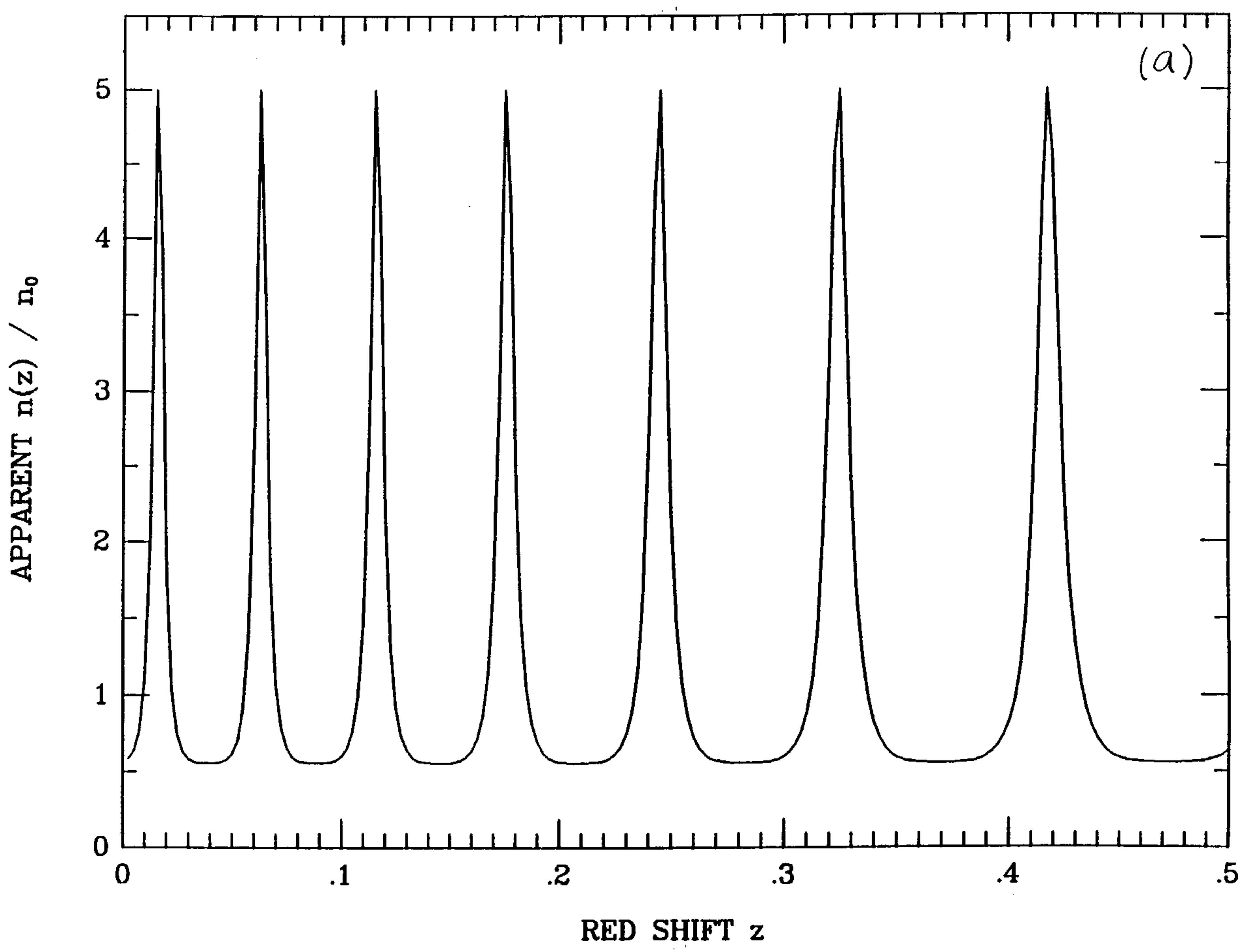
[1] For example, we have stated that Oklo provides the strongest limit on δm_e; however, with special assumptions, *e.g.*, $\delta m_e/m_e = -\delta m_\mu/m_\mu$, then the QED radiative correction to $\delta\alpha$ vanishes to lowest order and the Oklo limit on δm_e becomes impotent.

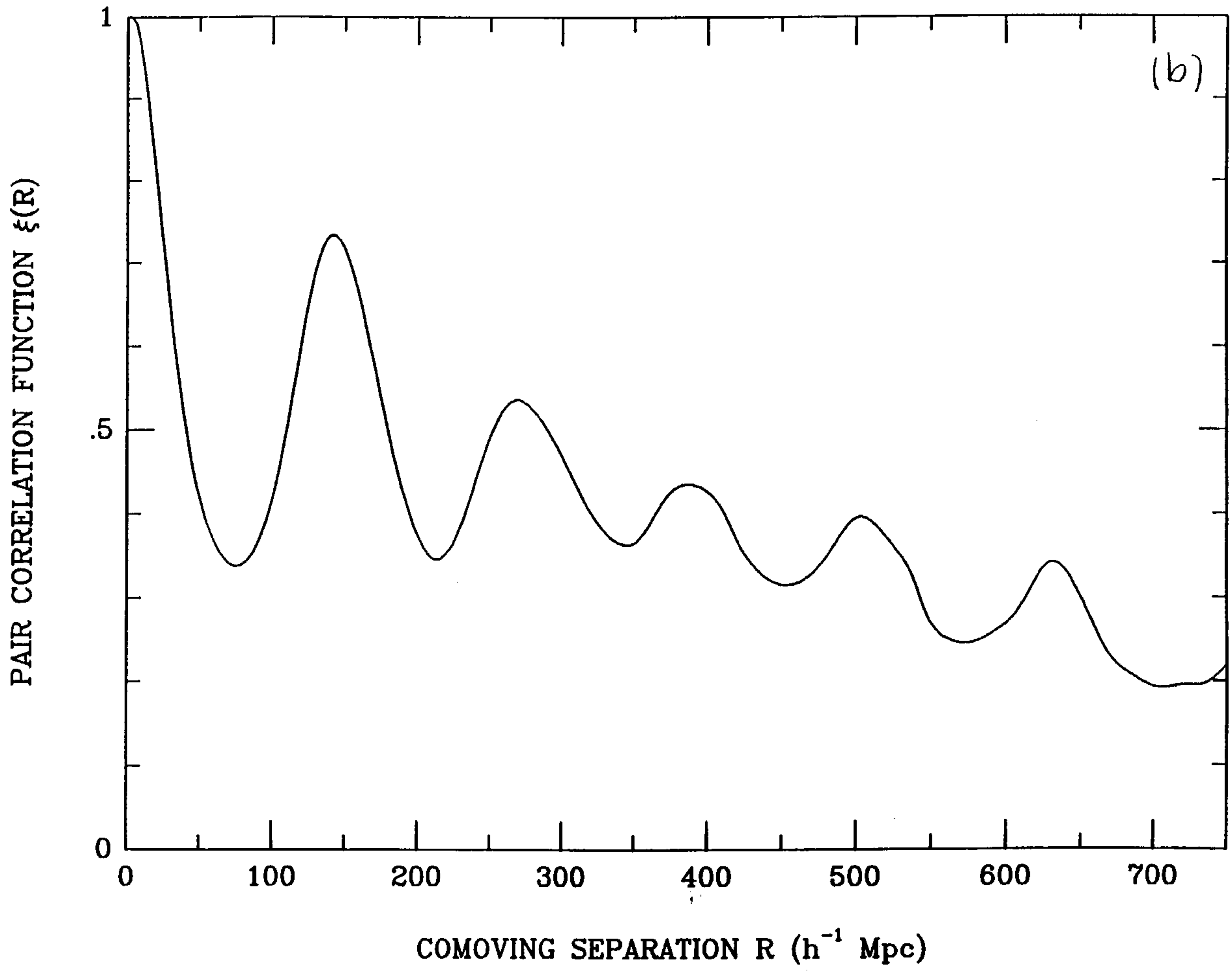
for example, weakly interacting particles (e.g., axion) whose masses and/or couplings oscillate coherently with time could produce periodic variations in the stellar energy balance and, hence, photon luminosity of one or more stellar populations.

An alternative, intriguing approach is to consider variations in couplings that might periodically cause the matter in the dark halos (or centers) of galaxies to "glow." For example, a neutrino halo could glow periodically if optical photons are produced in a reaction $\nu' \rightarrow \nu + X + \gamma$ whose rate varies due to mass oscillations in ν or ν'. The glowing of dark matter would have dramatic cosmological implications without affecting stellar evolution. A more thorough analysis of specific oscillating luminosity scenarios will be complicated and sensitive to the systematics of the BEKS survey. While such scenarios seem viable in principle, they are harder to judge than the simple scenarios presented above.

In sum, we find that an oscillating gravitational constant and oscillating galactic luminosities, either due to periodic variations in stellar luminosities or due to periodic "glowing" of dark halos, are the most viable candidates for generating an apparent periodicity in the galaxy distribution. Oscillating α or m_e may be ruled out by existing limits, though even this possibility merits further scrutiny. We remark that oscillations—regardless of source—provide precise time/distance "markers" in the Universe that could allow one to determine H_0, q_0 and Ω_0. While oscillating physics is admittedly a very radical and speculative idea, we wish to stress the virtue that it is readily testable both by a variety of near-term cosmological observations and by precision laboratory experiments. The first critical test, for which data will exist within the next year or so, will be to see whether deep galaxy surveys ultimately reveal a red shift distribution peaked on approximately concentric spheres with periodically spaced radii. If so, one is led to the shocking conclusion that we lie at the center of an inhomogeneous Universe or the "merely radical" conclusion that we are observing an artifact of the oscillating physics described here.

Figure Caption Figure 1. (a) The modulation factor for the galaxy number density, $n(z)/n_0$, for $\mathcal{A} = 0.8$, $\psi = 0$ and period $L = 128\ h^{-1}$ Mpc. (b) The one-dimensional galaxy pair correlation function for a north/south polar survey using the distribution in (a).


(a)
APPARENT n(z) / n₀
RED SHIFT z
0
1
2
3
4
5
.1
.2
.3
.4
.5


(b)
PAIR CORRELATION FUNCTION ξ(R)
1
.5
0
0
100
200
300
400
500
600
700
COMOVING SEPARATION R (h^-1 Mpc)

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References

[1] Broadhurst, T. J., Ellis, R. S., Koo, D. C., and Szalay, A. S., *Nature* **343**, 726-728 (1990).

[2] Hill, C. T., and Ross, G. G., *Nucl. Phys.* **B311**, 253-297 (1988); *Phys. Lett* **203B**, 125-131 (1988).

[3] Morikawa, M., Univ. of British Columbia preprints 90-0208 and 90-0380 (1990).

[4] de Lapparent, V., Geller, M. J., and Huchra, J. P., *Astrophys. J.* **302**, L1-5 (1986).

[5] Wilkinson, D. T., in *13th Texas Symposium on Relativistic Astrophysics* ed. M. Ulmer, pp. 209-218 (WSPC, Singapore, 1987).

[6] Reasenberg, R.D., *et al.*, *Astrophys. J.* **234**, L219-221 (1979).

[7] La, D. and Steinhardt, P. J., *Phys. Rev. Lett.* **62**, 376-9 (1989); Steinhardt, P. J. , and Accetta, F. S., *Phys. Rev. Lett.*, **23**, 2740-3 (1990). The second paper discusses $\xi < 0$ as considered in Eq. 10 as a novel approach to induced gravity.

[8] Boshier, M.G., *et al.*, *Nature* **330**, 463-465 (1987); see also Cohen, E. R. and Taylor, B. N., *Rev. Mod. Phys.* **59** 1121-1148 (1987).

[9] Bahcall, J. N. and Schmidt M., *Phys. Rev. Lett.* **19**, 1294-5 (1967).

[10] Dyson, F.W., in *Aspects of Quantum Theory*, ed. A. Salam, E. P. Wigner, pp. 213–236 (Cambridge University Press, Cambridge,1972); *ibid.*, in *Current Trends in the Theory of Fields*, ed. J. E. Lannutti, P. K. Williams, pp. 163–167 (Amer. Inst. of Phys., New York, 1978).

[11] Tubbs, A. D. and Wolfe, A. M., *Astrophys. J.* **236**, L105-8 (1980); Brown R. L. and Mitchell, K. J., *Astrophys. J.* **264**, 87- (1983).

[12] D. Koo, private communication.